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Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing

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[1] A new multiobjective formulation is proposed for the optimal design and rehabilitation of a water distribution network, with minimization of life cycle cost and maximization of performance as objectives. The life cycle cost is considered to comprise the initial cost of pipes, the cost of replacing old pipes with new ones, the cost of cleaning and lining existing pipes, the expected repair cost for pipe breaks, and the salvage value of the pipes that are replaced. The performance measure proposed in this study is a modification to the resilience index to suit application to water distribution networks with multiple sources. A new heuristic method is proposed to obtain the solution for the design and rehabilitation problem. This heuristic method involves selection of various design and rehabilitation alternatives in an iterative manner on the basis of the improvement in the network performance as compared to the change in the life cycle cost on implementation of the alternatives. The solutions obtained from the heuristic method are used as part of the initial population set of the multiobjective, nondominated sorting genetic algorithm (NSGA-II) in order to improve the search process. Using a sample water distribution network, the modified resilience index proposed is shown to be a good indicator of the uncertainty handling ability of the network.

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1. Introduction

[2] The deterioration of water distribution system performance is influenced by changes in demand pattern and water quality standards over time, and the existing environmental conditions. This is reflected by increased interruptions to customers due to higher pipe breakage rates, lower hydraulic capacities due to increase in roughness of pipes, and reduction in quality of the water received. Traditionally, water distribution networks were designed without considering the optimal rehabilitation strategy and the rehabilitation of the network was need based (in case of network deterioration and increased demands) rather than preplanned. A few of the typical works on optimal design of water distribution networks include *Alperovits and Shamir* [1977], *Gessler and Walski* [1985], *Goulter and Morgan* [1985], *Fujiwara and Khang* [1990], *Simpson et al.* [1994], *Savic and Walters* [1997], *Vairavamoorthy and Ali* [2000]. However, since high initial investments may result in a low maintenance and rehabilitation cost, while compromising on the initial investment may lead to increased rehabilitation costs, it is prudent to consider the design and the rehabilitation processes together, in order to arrive at the optimal strategy that maximizes the performance of the network during its service life, while minimizing the life cycle cost. This involves simultaneously determining the initial state of the network and devising an appropriate rehabilitation strategy to maintain the performance of the network above a threshold level throughout its service life.

[3] The deterioration of a network with age has been well studied in the past. *Shamir and Howard* [1979] reviewed various methods used for predicting the deterioration in the structural capacity of pipes with age. They reported the following regression equation to fit the breakage data well:

$$BR(t) = BR(t_0)e^{A(t-t_0)} \tag{1}$$

where $BR(t)$ is the number of breaks per unit length in year t; $BR(t_0)$ is the initial break rate per unit length of the pipe; t is the time in years; t_0 is the base year for the analysis (the year in which the pipe was installed) and A is the growth rate coefficient. *Shamir and Howard* [1979] reported the range of the rate coefficients for pipe breaks to be between 0.05 and 0.15.

[4] Yet, structural capacity deterioration is not the sole factor that determines the network rehabilitation schedule. As the network ages, since, the hydraulic capacity of the network decreases, replacement and/or cleaning and lining of pipes would be necessary to restore the hydraulic capacity of the network. *Sharp and Walski* [1988] reviewed various methods for predicting the roughness growth rate in pipes. They reported that the roughness (e) of a pipe increases linearly with age and that the roughness of a pipe

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at age t would be the sum of its initial roughness and the product of roughness growth rate (a) and the age of the pipe (equation (2)):

$$e = e_0 + at \tag{2}$$

An initial pipe roughness of 0.18 mm has been suggested as a default value, in the absence of adequate data. *Sharp and Walski* [1988] also provided a relationship between the Hazen-Williams coefficient and the internal roughness of the pipe which is as follows:

$$C = 18.0 - 37.2 \times \log\left(\frac{e}{D}\right) \tag{3}$$

where D is the diameter of the pipe. Combining equations (2) and (3), hydraulic deterioration of pipe network can be obtained (in terms of the Hazen-Williams coefficient).

[5] A number of options exist for rehabilitation action, namely replacement, duplication, relining, cleaning, cleaning and lining, and other techniques such as detection techniques and pressure reduction schemes. The choice of the rehabilitation action depends on the cost and the benefit of each option. Most commonly chosen options are replacement and cleaning and lining. These two options have been included in this study as well.

[6] The water distribution network rehabilitation-planning problem has been attempted in the past by several researchers. *Shamir and Howard* [1979] developed an analytical approach to solve the pipe replacement problem. They expressed the pipe break growth rate and hence the expected pipe break repair cost as an exponential function. The replacement age of the pipe is that at which pipe replacement would minimize the present value of the total cost (sum of the present values of replacement costs and repair costs), which was obtained analytically. However, this method doesn't consider the hydraulic performance of the network. In fact, a rehabilitation strategy must ensure hydraulic performance after rehabilitation, meet water quality guidelines and provide reliable service with minimum interruptions.

[7] An effective rehabilitation strategy should provide optimal tradeoffs between economic, hydraulic, reliability and water quality performance criteria. Rehabilitation decision models in the literature have been classified by *Engelhardt et al.* [2000] as (1) general rehabilitation guidelines, (2) prioritization models, and (3) optimization models. A detailed review of these decision models has been provided by *Engelhardt et al.* [2000]. The general rehabilitation guideline–based models made no attempt to prioritize the rehabilitation requirements. Also, the assessment was centered around a single performance measure. Although the prioritization models are suited for the whole-life costing ideology, they do not explicitly account for the budget and are not able to consider extended planning horizons. Moreover, the levels of service (performance) that would be provided by the system after rehabilitation cannot be predicted. Multiobjective optimization approaches are found to overcome the drawbacks of the other two models mentioned and can be utilized effectively to formulate whole life costing models that can provide optimal tradeoffs between economic, hydraulic, reliability and water quality performance criteria [*Engelhardt et al.*, 2000].

[8] *Halhal et al.* [1997] solved the network rehabilitation problem measuring the improvement in network performance on rehabilitation using a benefit function, which was computed as a weighted average of hydraulic benefit, physical integrity benefit, flexibility benefit and quality benefit. They also stated that conventional optimization techniques are poorly suited to handle the problem of choosing optimal network improvements and hence used a structured messy genetic algorithm (SMGA) to arrive at the trade-off between capital cost and benefit for the rehabilitation problem.

[9] *Kleiner et al.* [1998a, 1998b, 2001] deal with the network renewal-planning problem in which, both the structural and the hydraulic capacity deterioration of the network are considered in obtaining the optimal rehabilitation schedule. An initial estimate of the optimal age at which a pipe needs to be replaced is obtained solely on the basis of the structural costs. This age is termed the minimum cost replacement time (MCRT). Following this, the evaluation and selection of the rehabilitation alternatives are done on the basis of both structural and hydraulic conditions in a staged manner. However, this method assumes identical replacement cycles in the calculation of MCRT. Moreover, the algorithm is a heuristic technique based on partial enumeration and hence may not be able to easily handle large networks (as acknowledged by the authors themselves).

[10] *Sægrov et al.* [1999] have surveyed the research needs and ongoing efforts with regard to the rehabilitation of water networks in Europe and North America. The use of statistical methods for estimating the present and the future rehabilitation needs, and the use of software tools for prioritizing rehabilitation actions have been discussed. The need for the assessment of structural condition of pipes as part of a proactive approach is brought out in comparison with a reactive approach of locating the leaks and repairing them. The necessity of a decision support system to select and schedule the rehabilitation alternatives considering total cost, deterioration in structural integrity and hydraulic capacity, reliability of the network, risk factors including water quality issues, is brought out. Also, a framework for exploring the rehabilitation needs and strategies is suggested. For future investments, the whole life costing (WLC) approach is advocated.

[11] *Engelhardt et al.* [2002] and *Skipworth et al.* [2003] developed a whole life costing (WLC) framework for determining long-term maintenance expenditure requirements for water distribution networks. They provide a rigorous frame work to estimate the costs arising from the operation, maintenance and management of a water distribution network. They include operational costs, capital expenditure (cost of replacement), public costs (social and environmental costs) and costs associated with leakage and pipe bursts. They also consider factors such as demand projections, leakage, changes in hydraulic capacity and structure capacity, customer interruptions and water quality through interconnected modules. A decision tool and GIS are also integrated into the framework. *Engelhardt et al.* [2002] also describe a software, WiLCO, based on the above WLC framework, which uses GA to determine the best maintenance profile to meet a given set of objectives, for the specified performance constraints. However, the above research works including *Engelhardt et al.* [2002]

and *Skipworth et al.* [2003] aim to obtain the optimal rehabilitation strategy of an existing water distribution network considering the maintenance and operation issues and do not focus on arriving at the optimal strategy for design and rehabilitation together.

[12] The performance assessment of a water distribution system can be defined in terms of the probability that the system is operational (reliability), the percent of time that the system is operational (availability), or in terms of indices or surrogate measures that are determined to reflect the operational requirements of the system (serviceability). The common approaches used for quantifying these performance measures are Monte Carlo simulation, path enumeration and state enumeration [*Engelhardt et al.*, 2000]. A detailed review of various performance measures used in water distribution networks can be found in works by *Goulter et al.* [2000], *Engelhardt et al.* [2000], and *Jayaram* [2006].

[13] The works of *Shamir and Howard* [1979] and *Kleiner et al.* [2001] assume that the nodal demands and the pipe roughness coefficients are known deterministically throughout the service life of the network. However, a number of uncertainties exist at the planning stage, which include demand uncertainty and hydraulic uncertainty. Researchers, in the past, have proposed various measures of network reliability in order to account for these, in the context of the water distribution network design problem and to an extent, the water distribution network rehabilitation problem. *Xu and Goulter* [1999] represented the nodal demands and the pipe hydraulic capacities as probabilistic variables and computed the probability that the nodal head at the most critical node would be above the specified nodal pressures using the first-order reliability method (FORM). *Tolson et al.* [2004] used the FORM in order to estimate the probability that nodal heads at the two most critical nodes would be higher than the minimum required nodal heads. FORM requires repetitive calculations of the first-order derivatives and matrix inversions, and hence computationally demanding [*Kapelan et al.*, 2005]. *Kapelan et al.* [2005] computed the probability of simultaneously satisfying the minimum pressure head constraints at all nodes in the network using the Latin hypercube sampling technique. It may not be appropriate to use these approaches in the context of a design and rehabilitation problem, in which, the performance of the network needs to be tracked over its entire service life for the following reasons: (1) uncertainty in the identification and characterization of probability density functions of nodal demands and pipe roughness coefficients in every year and (2) enormous computation load involved in computing the reliability measures based on FORM or sampling techniques. Hence it may be practical to use simpler and surrogate measures of reliability in the life cycle–based design and rehabilitation problem.

[14] Several surrogate reliability measures have been used in the past in the context of the water distribution network problems. One of the commonly used indicators of reliability is the minimum surplus head available in a network [*Prasad and Park*, 2004]. The surplus head at a node refers to the excess of the available head at a node over the minimum required head. *Park et al.* [1998] defined a performance measure termed hydraulic power capacity, which is the probability that there exists a feasible flow of hydraulic power in the water distribution network. However, the computation of this measure requires assumptions regarding the total minimum network loss of power (assumed to be a known fraction of the output power flow) and regarding subsequent redistribution of the power loss to the nodes (based on parameters of the links connecting to the nodes). Moreover, the computation of hydraulic power capacity requires the use of Monte Carlo simulations, which increases the computing time.

[15] *Todini* [2000] introduced the concept of resilience index as an indicator of the ability of the network to cope with uncertainties. Resilience index is defined as the ratio of surplus internal power in the network to the maximum power that could be dissipated internally, while still satisfying the constraints on nodal demands and nodal heads. *Todini* [2000] also stated that providing higher surplus heads and power at the nodes may help the network perform under abnormal conditions on account of the additional energy that is available for dissipation in such cases.

[16] *Dandy and Engelhardt* [2006] obtain the trade-off between cost and a reliability measure using multiobjective genetic algorithm. This method involves the identification of the optimal pipe replacement schedule for an existing network, that minimizes the cost and the expected number of customer interruptions due to pipe breaks over the service life of the network (termed TENCI). In this method, it is assumed that the pipes can be replaced at any prespecified time step over a defined planning horizon, though the diameter of the pipes is considered to remain the same after replacement. However, it does not consider the hydraulic capacity deterioration of the network and hence the pipe rehabilitation option of cleaning and lining of pipes. Moreover, the TENCI values have been computed prior to the implementation of the GA and this is facilitated by the assumption of fixed pipe diameters which may not always be true. Further, the computation of the TENCI values would be more complex if increases in nodal demands and hydraulic deterioration of the network with time are to be considered.

[17] *Farmani et al.* [2005] have used the improved nondominated sorting genetic algorithm method (NSGA-II) [*Deb et al.*, 2002] to handle three objectives, namely, (1) the total cost of network expansion and rehabilitation that include capital expenditure and pumping costs, (2) the resilience index of *Todini* [2000], and (3) the minimum surplus nodal head while obtaining the optimal expansion and rehabilitation strategy for the ‘‘Anytown’’ network.

[18] However, it can be shown that the resilience index of *Todini* [2000] does not accurately reflect the ability of the network to handle uncertainties in case of networks with multiple sources. In the present study, the resilience index proposed by *Todini* [2000] has been modified to obtain a performance measure termed modified resilience index, which can be used in networks with single or multiple sources.

[19] *Farmani et al.* [2005] have reported NSGA-II to be appropriate for water distribution network optimization problems involving constraints, since it is found to satisfy the primary goals of Pareto multiobjective optimization, namely, nearness to the global Pareto-optimal front and diversity among the solutions on the front. However, when life cycle cost is considered as an objective as against the

cost incurred at a single point in time, there would be a substantial increase in the number of decision variables and a large increase in the number of hydraulic simulations that would have to be carried out. In such complex problems, the search process of a genetic algorithm originating from a randomly generated population set may not be effective in terms of arriving at the nondominant front in a computationally efficient manner. The search process of a genetic algorithm for the optimal design and rehabilitation problem considering life cycle costing may be improved by introducing a small number of diverse solutions obtained using a computationally efficient heuristic method, into the initial population set of the genetic algorithm. In this regard, a new heuristic method has been proposed in this work to solve the optimal design and rehabilitation problem. This heuristic method involves the selection of various design and rehabilitation alternatives in an iterative manner, based on the improvement in the network performance, as compared to the change in the life cycle cost on implementation of the alternatives.

[20] In the present study, a multiobjective formulation is proposed for the optimal design and rehabilitation of a network, with minimization of life cycle cost and maximization of minimum modified resilience index over the service life of the network as objectives. The modified resilience index is proposed as an improvement over the resilience index of *Todini* [2000], in terms of applicability to networks with multiple sources. The EPANET2 is used as the simulating engine to evaluate the modified resilience index values of the network during its service life and the nondominated sorting genetic algorithm (NSGA-II) proposed by *Deb et al.* [2002] is used to solve the constrained, multiobjective optimization problem. A new heuristic method is proposed in this study for use in design and rehabilitation problems that aim to maximize network performance while minimizing the life cycle cost. This heuristic method is shown to yield a set of diverse initial solutions, that when fed to the NSGA-II, drives the search process of the NSGA-II to reach the Pareto optimality in far less number of generations, leading to significant reduction in computing time. A sample network from *Larock et al.* [1999] is used to illustrate the optimal design and rehabilitation model proposed.

2. Modified Resilience Index

[21] Although the resilience index introduced by *Todini* [2000] is a simple and useful measure of the network performance, it may not be appropriate for use, if multiple sources are present in the network. Hence this index has been modified in the present study to enable applications that involve networks with multiple sources as well.

[22] The resilience index introduced by *Todini* [2000] is the ratio of the surplus internal power in the network to the maximum power that could be dissipated internally, after satisfying the constraints on nodal demands and nodal heads and is given as

$$I_r = 1 - \frac{P_{int}}{P_{int,\max}} \tag{4}$$

where P_{int} is the amount of power dissipated internally in the network in order to satisfy the nodal demands and $P_{int,\max}$ is the maximum power that could be dissipated internally in order to satisfy the constraints in terms of nodal demands and the nodal heads. P_{int} is calculated as follows:

$$P_{int} = P_{tot} - \gamma \sum_{j=1}^{nn} Q_j^{req} H_j \tag{5}$$

where Q_j^{req} is the demand at node j; H_j is the head at node j; γ is the specific weight of water and nn is the number of nodes. P_{tot} is the total power available at the entrance of the water distribution network, which equals $\gamma \sum_{r=1}^{nr} Q_r H_r$, where Q_r is the discharge delivered by the reservoir r and H_r is the head at the reservoir r and nr is the number of reservoirs feeding the network. $P_{int,\max}$ is calculated as follows:

$$P_{int,\max} = P_{tot} - \gamma \sum_{j=1}^{nn} Q_j^{req} H_{\min,j} \tag{6}$$

where $H_{\min,j}$ is the minimum required head at node j at which the nodal demands are to be supplied.

[23] On substituting the values of P_{int} (equation (5)) and $P_{int,\max}$ (equation (6)) in equation (4), the resilience index (for networks without pumps) can be written as

$$I_r = \frac{\sum_{j=1}^{nn} Q_j^{req} \left(H_j - H_{\min,j}\right)}{\sum_{r=1}^{nr} Q_r H_r - \sum_{j=1}^{nn} Q_j^{req} H_{\min,j}} \tag{7}$$

It can be observed from equation (7), that the term $\sum_{r=1}^{nr} Q_r H_r$ needs to be computed in order to obtain the resilience index. For networks with a single reservoir (r = 1), the terms $Q_1 H_1$ and $\sum_{j=1}^{nn} Q_j^{req} H_{\min,j}$ remain constant irrespective of the pipe diameters and pipe roughness values and hence the value of resilience index is directly proportional to the surplus power in the demand nodes $\left(\sum_{j=1}^{nn} Q_j^{req} (H_j - H_{\min,j})\right)$. However, in networks with multiple sources, the flow output from the sources (Q_r) and hence the term $\sum_{r=1}^{nr} Q_r H_r$, present in the denominator of equation (7), are not independent of the pipe diameters and pipe roughness values. This implies that a network with a large surplus power at the demand nodes may also have a large input power value and thereby, a low value of resilience index. For instance, when the diameter of a pipe connected to a reservoir that operates at a higher HGL value as compared to the other reservoirs is increased, it is likely that a larger portion of the total demand would be served by this reservoir than before. This would result in an increase in the $\sum_{r=1}^{nr} Q_r H_r$ value in addition to the possible increase in the value of $\sum_{j=1}^{nn} Q_j^{req} (H_j - H_{\min,j})$. This may result in a low value of resilience index despite a high value of surplus power at the demand nodes.

[24] In this work, the network performance measure, resilience index, proposed by *Todini* [2000], has been modified, rectifying the above mentioned drawback in the resilience index. The modified resilience index is based on the premise that the intent of a designer is to provide

additional power at the demand nodes than what is normally required in order to handle uncertainties. The surplus power provided at the nodes of the network would ensure that additional power could be dissipated in the network in case of enhanced demands or unexpected deterioration of the network. This measure proposed is termed modified resilience index (MI_r), and is defined as the amount of surplus power available at the demand nodes as a percentage of the sum of the minimum required power at the demand nodes:

$$MI_r = \frac{\sum_{j=1}^{nn} Q_j^{req}\left(H_j - H_{\min,j}\right)}{\sum_{j=1}^{nn} Q_j^{req} H_{\min,j}} \times 100 \tag{8}$$

[25] It can be seen from equation (8) that the value of the modified resilience index is directly proportional to the total surplus power at the demand nodes. The term $\sum_{j=1}^{nn} Q_j^{req} H_{\min,j}$ is used to nondimensionalize the value of the surplus power at the demand nodes. The above definition can be extended for use in networks with pumps and tanks.

[26] It is to be noted that the interpretation of the modified resilience index is similar to that of the resilience index. While the resilience index takes values up to a maximum of 1, the modified resilience index can be greater than 1 with a theoretical upper limit of infinity (although infinity may not occur in practice). A modified resilience index value of X implies that the power at the demand nodes exceeds the minimum required power at the demand nodes by X%. A higher value of X indicates a larger quantity of surplus power at the demand nodes, and thereby a better ability to handle uncertainties. So, the modified resilience index could be used to compare the uncertainty handling of one network relative to another, which is essential in the design and rehabilitation problems. For a more detailed analysis, Monte Carlo simulation (considering variables such as demand, roughness coefficient to be random) could be used to evaluate the solutions from the nondominant front obtained, before a final solution is selected for implementation.

3. Formulation

[27] The objective of the problem is to determine the least cost solution (present value of the life cycle cost) to a typical network design and rehabilitation problem, while maximizing the minimum value of the modified resilience index over the service life of the network with an intent to cater to the uncertainties. The process of design is considered to involve the determination of the initial pipe diameters, while the process of rehabilitation of the network is considered to involve cleaning and lining and/or replacement of one or more pipes in the network at different points in time during the network's service life. Moreover, the diameter of a pipe after replacement can take any of the commercially available sizes. In this formulation, an upper limit is fixed on the number of times a pipe could be replaced (n_1) and the number of times a pipe could be cleaned and lined (n_2). There are hence ($1 + 2n_1 + n_2$) decision variables corresponding to each pipe in the network, namely, the initial diameter, the n_1 years in which the pipe is to be replaced, the n_1 pipe diameters corresponding to the n_1 years of pipe replacement, the n_2 years in which the pipe should be cleaned and lined. A multiobjective formulation for the optimal design and rehabilitation problem considered is proposed herein.

[28] The two objectives of the optimal design and rehabilitation formulation are (1) to minimize the present value of life cycle cost of the network and (2) to maximize minimum resilience index over the service life of the network.

3.1. Minimize the Present Value of the Life Cycle Cost

[29] The life cycle cost of a network includes: (1) the initial cost of pipes, (2) the cost of replacing old pipes with new ones, (3) the cost of cleaning and lining existing pipes, (4) the expected repair cost for pipe breaks and (5) the salvage value of the pipes that are replaced. Since the cost of cleaning and lining, the cost of pipe replacement, the repair cost and the salvage value of pipes accrue at various points in time during the service life of the network, they need to be converted to the corresponding present value using a suitable discount rate, as shown in equation (9):

$$\begin{aligned}\text{Minimize } f_1 = {} & \sum_{p=1}^{np} IC\left(p, D_p^{new}\right) + \sum_{p=1}^{np} \sum_{t_p^{rep} \in R_p} RC\left(p, D_{p,t_p^{rep}}^{rep}, t_p^{rep}\right) \\ & + \sum_{p=1}^{np} \sum_{t_p^{c} \in C_p} CC\left(p, D_{p,t_p^c}, t_p^c\right) \\ & + \sum_{p=1}^{np} \sum_{t=1}^{SL} BC\left(p, D_{p,t}, BR_{p,t}, t\right) \\ & - \sum_{p=1}^{np} \sum_{t_p^{rep} \in R_p} SV\left(p, D_{p,t_p^{rep}-1}, t_p^{rep}, t_p^{rep,prev}\right)\end{aligned} \tag{9}$$

where p denotes a pipe, D_p^{new} is the initial diameter of the pipe p; t_p^{rep} is one of the years in which the pipe p would be replaced and $t_p^{rep,prev}$ is the year of previous replacement of pipe p; R_p is the set of all years in which the pipe p would be replaced; $D_{p,t_p^{rep}}^{rep}$ is the diameter of the pipe p after replacement in the year t_p^{rep}; t_p^c is one of the years in which pipe p would be cleaned and lined; C_p is the set of all years in which the pipe p would be cleaned and lined; D_{p,t_p^c} is the diameter of the pipe p to be cleaned and lined in the year t_p^c; $D_{p,t}$ is the diameter of pipe p in year t; $BR_{p,t}$ is the break rate of the pipe p in year t and SL is the service life of the network.

3.1.1. Initial Cost (IC)

[30] The initial cost of a pipe is given as

$$IC\left(p, D_p^{new}\right) = UC_p^{new}\left(D_p^{new}\right) L_p \tag{10}$$

where L_p is the length of the pipe p and UC_p^{new} (D_p^{new}) is the unit cost of a new pipe with diameter D_p^{new}.

3.1.2. Replacement Cost (RC)

[31] The replacement cost corresponds to the cost of new pipes that are used as replacement for the older ones. It is

assumed that pipes would be replaced at the beginning of the year. The total replacement cost is calculated as follows:

$$\text{Total replacement cost} = \sum_{p=1}^{np} \sum_{t_p^{rep} \in R_p} RC\left(p, D^{rep}_{p,t_p^{rep}}, t_p^{rep}\right) \tag{11}$$

In equation (11),

$$RC\left(p, D^{rep}_{p,t_p^{rep}}, t_p^{rep}\right) = \frac{UC_p^{new}\left(D^{rep}_{p,t_p^{rep}}\right)L_p}{\left(1+\frac{r}{100}\right)^{t_p^{rep}-1}}, \qquad t_p^{rep} > 1$$

where r is the discount rate.

3.1.3. Cleaning and Lining Cost (CC)

[32] The cleaning and lining cost corresponds to the cost of cleaning and lining of the existing pipes. It is assumed that the cleaning and lining of pipes would be carried out at the beginning of the year. The total cost of cleaning and lining is calculated as follows:

$$\text{Total cost of cleaning and lining} = \sum_{p=1}^{np} \sum_{t_p^c \in C_p} CC\left(p, D_{p,t_p^c}, t_p^c\right) \tag{12}$$

In equation (12),

$$CC\left(p, D_{p,t_p^c}, t_p^c\right) = \frac{UC_p^{cl}\left(D_{p,t_p^c}\right)L_p}{\left(1+\frac{r}{100}\right)^{t_p^c-1}}, \qquad t_p^c > 1$$

where $UC_p^{cl}(D_{p,t_p^c})$ is the unit cost of cleaning and lining pipe p with diameter D_{p,t_p^c}.

3.1.4. Breakage Cost (BC)

[33] The breakage cost corresponds to the expected cost for repairing pipe breaks. The breakage cost would be a function of the diameter of the pipe, the initial pipe break rate ($BR(t_0)$) and the growth rate in the pipe break rate (A). The breakage cost of a pipe during any year is assumed to be concentrated at the beginning of the year. The total cost of breakage is calculated as follows:

$$\text{Total breakage cost} = \sum_{p=1}^{np} \sum_{t=1}^{SL} BC\left(p, D_{p,t}, BR_{p,t}, t\right) \tag{13}$$

In equation (13),

$$BC\left(p, D_{p,t}, BR_{p,t}, t\right) = \frac{C_p^{repair} BR_{p,t} L_p}{\left(1+\frac{r}{100}\right)^{t-1}}$$

where C_p^{repair} is the cost of repairing a single pipe break for pipe p with diameter D_p; $BR_{p,t}$ is the expected number of breaks of pipe p during the year t_p per unit length of the pipe, which can be calculated by assuming an initial breakage rate and by using a break growth rate expression such as the one given by *Shamir and Howard* [1979].

3.1.5. Salvage Value (SV)

[34] The total salvage value is calculated as follows:

$$\text{Total salvage value} = \sum_{p=1}^{np} \sum_{t_p^{rep} \in R_p} SV\left(p, D_{p,t_p^{rep}-1}, t_p^{rep}, t_p^{rep,prev}\right) \tag{14}$$

In equation (14),

$$SV\left(p, D_{p,t_p^{rep}-1}, t_p^{rep}, t_p^{rep,prev}\right) = \frac{USV_p\left(D_{p,t_p^{rep}-1}, t_p^{rep,prev}\right)L_p}{\left(1+\frac{r}{100}\right)^{t_p^{rep}-1}}$$

where $USV_p\ (D_{p,t_p^{rep}-1}, t_p^{rep,prev})$ is the salvage value per unit length of the pipe p with diameter $D_{p,t_p^{rep}-1}$, which has been installed at the beginning of the year $t_p^{rep,prev}$ and is replaced at the beginning of the year t_p^{rep}.

3.2. Maximize Minimum Modified Resilience Index Over the Service Life Period

[35]

$$\text{Maximize } f_2 = \underset{SL}{\text{Min}} \left\{ MI_{r,t}(\mathbf{D_t}, \mathbf{C_t}, \mathbf{Q_t}) \right\} \quad t \in \left[t_{1,start}, t_{SL,end}\right] \tag{15}$$

where $MI_{r,t}$ ($\mathbf{D_t}$, $\mathbf{C_t}$, $\mathbf{Q_t}$) is the modified resilience index of the network in year t with diameter set ($\boldsymbol{D_t}$), set of Hazen-Williams coefficients ($\boldsymbol{C_t}$) and the nodal demand set ($\boldsymbol{Q_t}$); $t_{1,start}$ is the beginning of the first year; $t_{SL,end}$ is the end of the last year and SL is the service life of the network.

[36] In equation (15), f_2 denotes the minimum value of the modified resilience index that the network could possess during any of the years during its service life. The diameter of the pipes in any year needs to be calculated on the basis of the set of initial diameters, years in which pipe replacements are carried out and the diameters of the replaced pipes. The Hazen-Williams coefficient of the links would depend on the above mentioned factors and the years in which pipes are cleaned and lined, the initial pipe roughness and the roughness growth rate of pipes. The nodal demands in the network in any year would depend on the initial demands and the demand growth rate.

4. Solution Methods

[37] In this study, three methods are employed to solve the optimal network design and rehabilitation formulation. The first method involves the use of the multiobjective evolutionary algorithm, fast elitist nondominated sorting genetic algorithm II (NSGA-II) of *Deb et al.* [2002], to generate the trade-off between the two objectives. The second one involves the use of the proposed heuristic method. The third is a combination of the heuristic method and the NSGA-II. In this method, a small percent of the solutions obtained from the heuristic method are used as part of the initial population of the NSGA-II to drive the search process of the NSGA-II to reach the Pareto optimality in far less number of generations, leading to significant reduction in computing time. The following sections describe these three methods in detail.

4.1. Nondominated Sorting Genetic Algorithm II (NSGA-II)

[38] Figure 1 describes the methodology that uses NSGA-II to obtain the set of nondominated solutions for the optimal network design and rehabilitation problem proposed in this work. The objective functions and the constraint corresponding to each of the GA strings are to be evaluated in

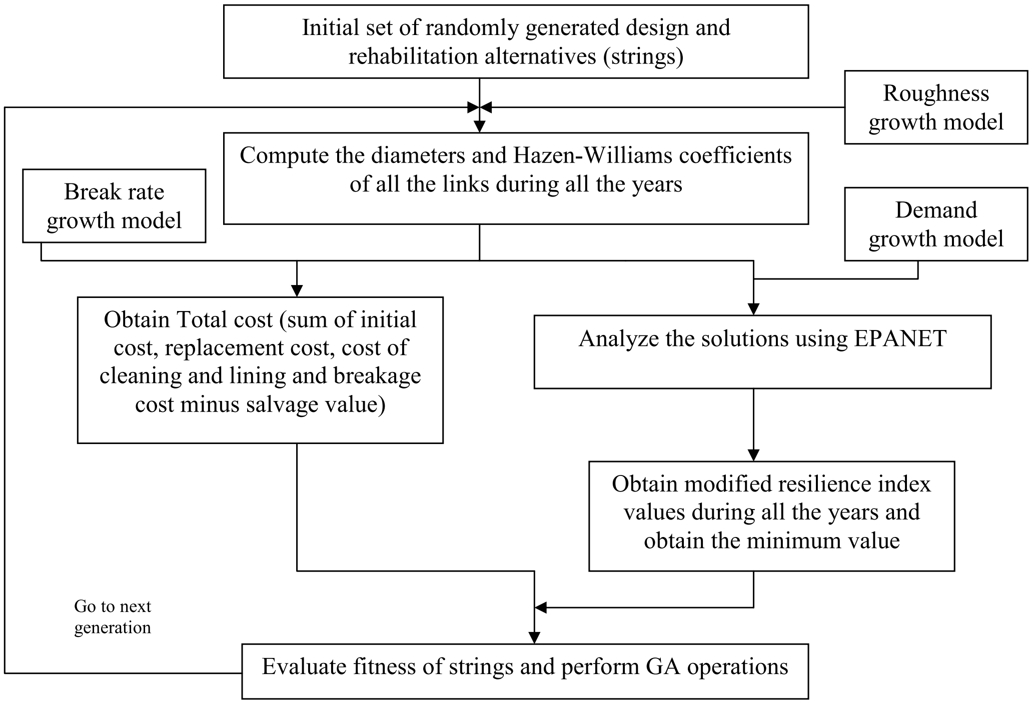

Figure 1. Solution methodology (using NSGA-II alone).

order to arrive at the fitness of the strings. Hence each of the network design and rehabilitation alternatives generated from the GA module is sent to the hydraulic network solver EPANET 2 [*Rossman*, 2000] for computing the nodal heads and subsequently, the minimum modified resilience index. Further, the life cycle cost corresponding to each design and rehabilitation alternative is computed using equation (9). Following this, the values of the objective functions are computed for all the network design and rehabilitation alternatives and are sent to the NSGA-II module for fitness function evaluation. After this, these solutions are sorted according to the fast elitist-based nondominated approach to identify the different levels of nondominated fronts. Subsequently new populations are created using binary tournament selection, crowded comparison, crossover and mutation. This process is repeated until the specified stopping criterion is achieved and the final set of nondominated design and rehabilitation alternatives is stored in an output file. Further discussions on the methodology of NSGA-II and its advantages over the other multiobjective evolutionary algorithms can be found in work by *Deb et al.* [2002] and *Murty et al.* [2006].

4.2. Heuristic Method

[39] It is envisaged to improve the search process of the NSGA-II by introducing in the initial population set of the genetic algorithm, a small number of diverse solutions obtained using a heuristic procedure for the optimal design and rehabilitation problem. In this regard, a new heuristic method is proposed to obtain the trade-off curve between the two objectives mentioned for the optimal design and rehabilitation problem.

[40] The proposed heuristic method initially assumes that the diameter of all the pipes would be equal to the smallest commercially available diameter throughout the entire service life of the network. Subsequently, the network configuration is updated in several iterations, each of which involves evaluating the consequences of various possible design and rehabilitation alternatives. The change in the life cycle cost and the improvement in the sum of the modified resilience index values in all the years $\left(\sum_{t=1}^{SL}\left(MI_r^{new,t} - MI_r^{old,t}\right)\right)$ ($MI_r^{new,t}$ is the modified resilience index of the network in the year t after implementing the design/rehabilitation alternative and $MI_r^{old,t}$ is the modified resilience index of the network in the year t before implementing the alternative) on implementing each of the alternatives is computed. The alternative that results in the largest improvement in the sum of the modified resilience index during the service life of the network as compared to the change in the life cycle cost is implemented in every iteration. This process is repeated until no further increase in the modified resilience index can be achieved.

[41] The detailed description of the proposed heuristic method is as follows. This heuristic method has also been illustrated in Figure 2.

[42] Let $D_{p,t}$ represent the diameter of pipe p in year t; $C_{p,t}$ be the Hazen-Williams coefficient of pipe p in year t; $BR_{p,t}$ be the breakage rate of pipe p in year t; $S_{p,t}^{cl}$ be the cleaning and lining status of the pipe p in year t ($S_{p,t}^{cl} = 1$ if pipe p is cleaned and lined in year t, $S_{p,t}^{cl} = 0$ else); and $S_{p,t}^{rep}$ be the replacement status of the pipe p in year t ($S_{p,t}^{rep} = 1$ if pipe p is replaced in year t, $S_{p,t}^{rep} = 0$ else).

[43] Step 1: To start with, assume that every link would have the smallest commercially available diameter pipe through out the entire service life of the network. At this stage, none of the pipes have been cleaned and lined or replaced at any point in time.

$$\begin{aligned} D_{p,t} &= D_{\min} \quad \forall\, p,t; \quad S_{p,t}^{cl} = 0 \quad \forall\, p,t; \\ S_{p,t}^{rep} &= 0 \quad \forall\, p,t; \quad C_{p,1} = C^{new}\left(D_{p,1}\right) \quad \forall\, p \\ BR_{p,1} &= BR^{new}\left(D_{p,1}\right) \quad \forall\, p \end{aligned}$$

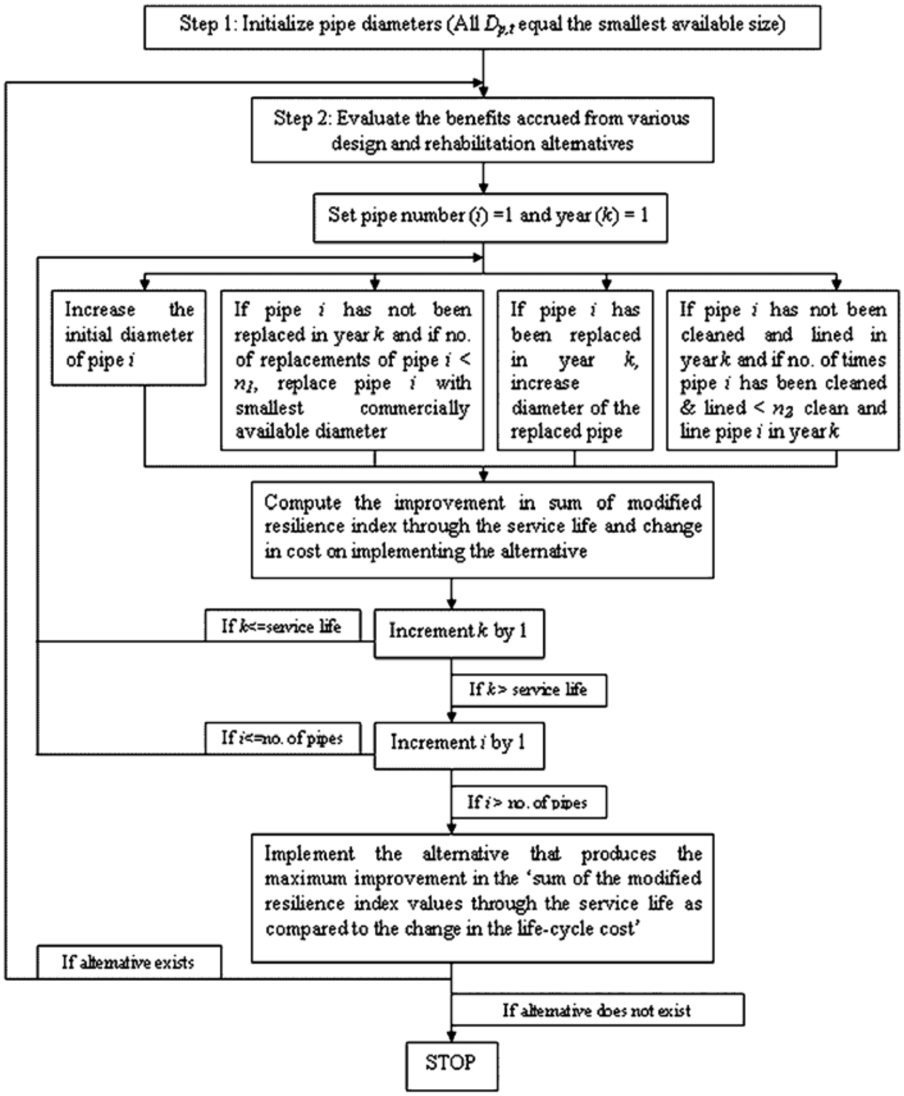

Figure 2. Solution methodology (using proposed heuristic alone).

where $D_{\min}$ is the smallest commercially available diameter; C^{new} $(D_{p,1})$ is the Hazen-Williams coefficient of a new pipe with diameter $D_{p,1}$ and BR^{new} $(D_{p,1})$ is the breakage rate of a new pipe with diameter $D_{p,1}$.

[44] Step 2: Evaluate the following design and rehabilitation alternatives on all the pipes in the network.

[45] 2.1: Evaluate the following actions on the pipe i in the network (Initial value of i equals 1).

[46] 2.1.1: Increase the initial diameter of the pipe i to the next commercially available size, if possible; that is, increase $D_{i,1}$ to the next available size. Compute and store the change in the life cycle cost and the change in the sum of the modified resilience index values in all the years. Reset the value of $D_{i,1}$ to the original value (the value that existed at the beginning of step 2). Proceed to 2.1.2.

[47] 2.1.2: Evaluate the following rehabilitation actions on pipe i carried out in the beginning of year k $\forall$ $k \in [2,$ *service life*] (Initial value of k equals 2).

[48] 2.1.2.1: If the pipe i has not been replaced in the year k (current year) in any of the previous iterations and if the number of times pipe i has been replaced in the previous iterations is less than the upper limit (n_1), replace the pipe i with the smallest commercially available diameter pipe in year k.

$$\text{If } S^{rep}_{i,k} = 0 \text{ and } \sum_{q=2}^{SL} S^{rep}_{i,q} < n_1, \text{ then,}$$
$$D_{i,r} = D_{\min} \qquad \text{for } r = k, k+1, \ldots, T_{next} - 1$$

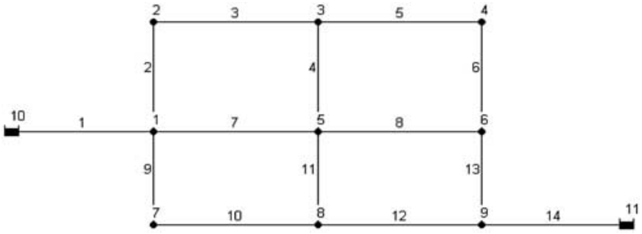

Figure 3. Sample network [*Larock et al.*, 1999].

Table 1. Node Parameters

Node	Demand in First Year, L/min	Elevation, m
1	2208.71	734.568
2	2038.81	733.044
3	1699.01	731.520
4	2378.62	713.232
5	1529.11	733.044
6	2548.52	716.280
7	2038.81	733.044
8	1699.01	731.520
9	2548.52	722.376

where T_{next} is the earliest year ($>k$) in which the pipe i is to be replaced as determined in the previous iterations.

$$C_{i,k} = C^{new}\left(D_{i,k}\right); BR_{i,k} = BR^{new}\left(D_{i,k}\right);\ S_{i,k}^{rep} = 1$$

Compute and store the change in the life cycle cost and the change in the sum of the modified resilience index values over the service life. Reset the values of the parameters that have been modified above to those that existed at the beginning of step 2. If $S_{i,k}^{rep} = 1$, then proceed to 2.1.2.2. If $S_{i,k}^{rep} = 0$ and $\sum_{q=2}^{SL} S_{i,q}^{rep} = n_1$, then proceed to 2.1.2.3.

[49] 2.1.2.2: If the pipe i has been previously replaced in year k, increase the diameter of the replaced pipe to the next commercially available size (if available). If $S_{i,k}^{rep} = 1$ and $D_{i,k} < D_{\max}$, then increment the value of $D_{i,r}$ to the next commercially available size for $r = k, k + 1, \ldots, T_{next} - 1$, where T_{next} is the earliest year ($>k$) in which the pipe i is to be replaced as determined in the previous iterations:

$$C_{i,k} = C^{new}\left(D_{i,k}\right); BR_{i,k} = BR^{new}\left(D_{i,k}\right)$$

where $D_{\max}$ denotes the largest available commercial diameter considered. Compute and store the change in the life cycle cost and the change in the sum of the modified resilience index values over the service life. Reset the values of the parameters that have been modified above to those that existed at the beginning of step 2.

$$\text{Else if } S_{i,k}^{rep} = 1 \text{ and } D_{i,k} = D_{\max}, \text{then proceed to 2.1.2.3}$$

[50] 2.1.2.3: If the number of times pipe i has been cleaned and lined in the previous iterations is less than the upper limit (n_2) and if the pipe has not been cleaned and lined in the year k in any of the previous iterations, clean and line the pipe i during the year k. If $S_{i,k}^{cl} = 0$ and $\sum_{q=2}^{SL} S_{i,q}^{cl} < n_2$, then $C_{i,k} = C^{cl}\ (D_{i,k})$; $S_{i,k}^{cl} = 1$, where $C^{cl}\ (D_{i,k})$ is the Hazen-Williams coefficient of a pipe with diameter $D_{i,k}$ after cleaning and lining. Compute and store the change in the life cycle cost and the change in the sum of the modified resilience index values over the service life. Reset the values of the parameters that have been modified above to those that existed at the start of step 2. Proceed to 2.1.3.

[51] 2.1.3: If k is less than the service life (SL) of the network, increment k by 1 and proceed to 2.1.2, else to 2.2.

[52] 2.2: If i is less than the number of pipes, increment i by 1 and proceed to 2.1, else to step 3.

[53] Step 3: Of all the options (listed in step 2) that are tried out on various pipes, implement the alternative that produces the maximum improvement in the sum of the modified resilience index values through the service life as compared to the change in the life cycle cost. If there is no change that can be deemed beneficial, the iteration is stopped and the heuristic method is terminated. Otherwise, go to step 2 and continue the iteration.

[54] Step 4: The various pairs of minimum modified resilience index and life cycle cost obtained in every iteration, at the end of step 3, form points on the trade-off curve.

4.3. Combination of NSGA-II and Heuristic Method

[55] In this section, a solution methodology is proposed to improve the search process of the NSGA-II, wherein a small number of diverse solutions obtained using the proposed heuristic method are incorporated in to the initial population set of the NSGA-II and the NSGA-II is rerun. Directing the search process of the NSGA-II from the solutions obtained using the heuristic method rather than a completely random set of solutions would drive the search process to reach the Pareto optimality in far less number of generations. The selection and the crossover mechanisms ensure that the fit strings (obtained using the heuristic method) that have been fed in to the initial population are used in arriving at new strings, which would then possess some of the characteristics of the fit strings. The elitism operator in the NSGA-II ensures that the solutions obtained from the heuristic method would continue to remain in the population set until better solutions are found during the search process of the NSGA-II. However, it is to be noted that only a small percent of the heuristic solutions are fed into the initial population of the NSGA-II with an intent to avoid any possible bias.

5. Case Example

[56] The multiobjective formulation proposed for the optimal network design and rehabilitation problem considered herein, is illustrated using a hypothetical network. The network topology is chosen from *Larock et al.* [1999] (Figure 3). This network consists of 11 nodes, where the nodes 10 and 11 refer to the source nodes with fixed hydraulic grade line (HGL) elevations of 792.48 m and 762 m respectively, while the remaining nodes (nodes 1 to 9) are demand nodes. The minimum HGL elevation

Table 2. Pipe Lengths

Link	Length, m
1	457.20
2	304.80
3	609.60
4	304.80
5	609.60
6	304.80
7	609.60
8	609.60
9	365.76
10	609.60
11	609.60
12	365.76
13	365.76
14	457.20

Table 3. Costs and Breakage Rate Data of Commercially Available Pipes

Diameter, mm	Cost of New Pipe[a]	Cost of Cleaning and Lining[a]	Break Rate of New Pipe, breaks/a/unit length
100	615	670.82	1.36
150	900	821.58	1.04
200	1290	948.68	0.71
250	1740	1060.66	0.39
300	2250	1161.90	0.07
350	2790	1254.99	0.05
400	3420	1341.64	0.05

[a] Cost is given in Indian rupees.

requirement at each demand node is assumed to be 15 m more than the nodal elevation. The values of the peak daily demands in the base year at the nodes along with the nodal elevations are given in Table 1. There are 14 links in the network, the lengths of which are given in Table 2.

[57] This network needs to be designed and maintained in good working condition for 30 a. It is assumed that there are 7 different sizes of commercially available pipes in the market, the costs and the breakage rate data of which are shown in Table 3.

[58] The initial roughness and the roughness growth of pipes are assumed on the basis of the data given by *Sharp and Walski* [1988] (equation (2)). The initial roughness of the pipes is assumed to be 0.18288 mm (0.0006 ft), while the pipe roughness growth rate is assumed to be 0.094488 mm/a (0.00031 ft/a). The initial break rate of pipes is assumed on the basis of the break data provided by *Goulter and Coals* [1986] and the break growth rate expression provided by *Shamir and Howard* [1979] (equation (1)) was used with the value of the break rate coefficient (A) taken to be 0.1. The cost of repairing a break is taken to be 1/50 of the unit cost of a new pipe. The performance of this network is expected to deteriorate over the life time of 30 a, not only because of the deterioration in the structural and the hydraulic capacities, but also because of the increase in nodal demands with time. It is assumed that the growth rates in all the nodal demands would be 2 percent/a.

[59] The two rehabilitation measures that have been adopted for this network are cleaning and lining of pipes and pipe replacements. The process of cleaning and lining is assumed to reduce the roughness of the pipe and thereby increase the hydraulic capacity. A cleaned and lined pipe is assumed to have a roughness value of 0.24384 mm (0.0008 ft). The costs of cleaning and lining pipes of various diameters are given in Table 3. Pipe replacements are assumed to reduce the roughness value of pipes and the break rate of pipes to those of a new pipe (Table 3). The salvage value of a pipe is calculated using linear depreciation:

$$\text{Salvage value} = \text{initial cost} \times (\text{residual life}/\text{total life})$$

where the total life is assumed to be 30 a and the residual life is taken to be 30 minus the number of years the pipe has served before replacement.

[60] It is also assumed that the upper limit of the number of pipe replacements (n_1) is 1 and the upper limit on the number of times a pipe can be cleaned and lined (n_2) is 2. In all present value computations, the real rate of return (nominal rate of return corrected for inflation) is taken as 5%.

[61] It is proposed to obtain the trade off between the life cycle cost and the minimum modified resilience index during the 30-a service period using (1) NSGA-II, (2) the proposed heuristic method, and (3) the combination of NSGA-II and the proposed heuristic method. It is also proposed to investigate the relationship between the modified resilience index and the ability of the network to handle uncertainties.

6. Results and Discussion

[62] The fallibility of the resilience index defined by *Todini* [2000] when applied to water distribution networks with multiple sources is illustrated using three different configurations A, B and C of the network shown in Table 4. In the configuration A, all the pipes in the network have a diameter of 300 mm with a Hazen-Williams coefficient of 100. In the configuration B, all the pipes in the network have a diameter of 400 mm with a Hazen-Williams coefficient of 100, while in C, all the pipes in the network have a diameter of 500 mm with a Hazen-Williams coefficient of 100. The nodal demands used for this analysis are taken to be the set of initial demands that are shown in Table 1. The terms, surplus output power at demand nodes, net input power (power at reservoirs that are draining minus power at reservoirs that are filling) and minimum output power required, that are used in the calculation of the resilience index and the proposed modified resilience index for the three configurations A, B and C are computed and shown in Table 4.

[63] It can be seen from the Table 4 that, as the diameter of the pipes increase from 300 mm (configuration A) to 500 mm (configuration C), the total surplus power at the demand nodes increases by nearly 52.2%, while the net input power also increases by around 6.4%. This increase in the total input power is a result of the redistribution of the flows supplied by the two reservoirs. In configuration A, the reservoir (node 10) with the higher head supplies

Table 4. Comparison of Solutions A, B, and C

Solution[a]	Pipe Hazen-Williams Coefficient	Surplus Output Power at Demand Nodes, kW	Net Input Power, kW	Minimum Output Power Required, kW	Resilience Index	Modified Resilience Index
A	100	61.33	2406.4	2266.3	0.43	2.65
B	100	78.50	2473.3	2266.3	0.38	3.46
C	100	91.56	2560.9	2266.3	0.31	4.04

[a] Solution A corresponds to a network configuration with all pipes having 300 mm diameter; solution B corresponds to a network configuration with all pipes having 400 mm diameter; and solution C corresponds to a network configuration with all pipes having 500 mm diameter.

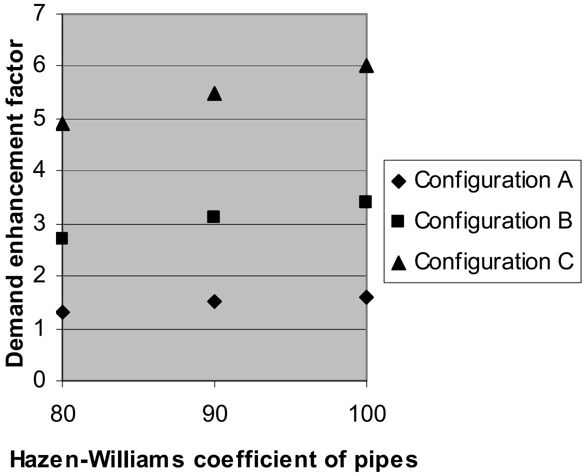

Figure 4. Comparison of the nodal demand enhancement factors corresponding to various Hazen-Williams coefficient values for the three solutions A, B, and C.

15.66 m^3/min of flow, while the reservoir (node 11) with the lower head supplies 3.03 m^3/min of flow. On the other hand, in configuration C, reservoir 10 supplies 46.65 m^3/min of flow, with the reservoir 11 receiving 27.96 m^3/min of flow. The increased supply from the reservoir with the higher head (node 10) in configuration C results in an increase in the net input power in configuration C as compared to configuration A. This increase in the net input power results in an overall reduction in the value of the resilience index, with an increase in the diameter of the links from 300 mm to 500 mm, even though the latter configuration has a higher total surplus output power at the demand nodes than the former. Further, in order to compare the performance of configurations A, B and C under demand and hydraulic uncertainty, the maximum demand enhancement, at which, all nodal heads would remain above the minimum required value, for different values of reduced Hazen-Williams coefficients of all the links are found. The nodal demand enhancement was simulated by multiplying all the nodal demands by an enhancement factor (α), while the deterioration of the hydraulic capacity of the pipes was introduced through a reduction (β) in the Hazen-Williams coefficients:

$$\begin{aligned} Q_j^{enh} &= Q_j \times \alpha, \; j = 1, 2, \ldots, nn \\ C_p^{red} &= C_p - \beta, \; p = 1, 2, \ldots, np \end{aligned} \tag{16}$$

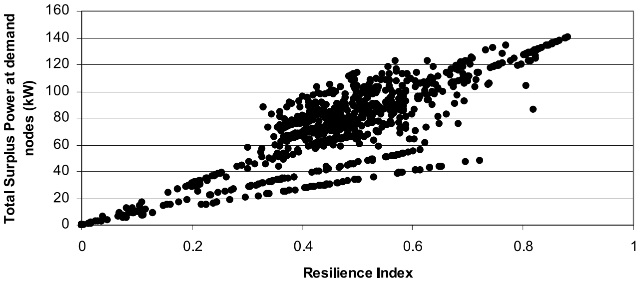

Figure 5. Scatterplot of total surplus power at demand nodes and resilience index [of *Todini*, 2000] for 1000 randomly generated network configurations.

where Q_j^{enh} is the enhanced value of nodal demand at node j; C_p^{red} is the reduced value of the Hazen-Williams coefficient of pipe p and β is the reduction in the Hazen-Williams coefficient of the pipes.

[64] Figure 4 shows the comparison of the maximum nodal demand enhancement factor at which the head requirements are satisfied at all nodes, for different values of pipe Hazen-Williams coefficient (C_p^{red}), for the three network configurations. It can be observed from Figure 4 that, despite the low value of resilience index (as defined by *Todini* [2000]), configuration C can handle enhanced demands and deteriorated hydraulic conditions much better than network A. This is a result of the additional surplus total output power in configuration C as compared with A, which is reflected by the high modified resilience index value in case of solution C.

[65] In order to further substantiate the above conclusion, 1000 network configurations (with pipe diameters ranging between 100 mm and 500 mm, retaining the Hazen-Williams coefficient of all the pipes to be 100) were randomly generated and their resilience index [of *Todini*, 2000] and total surplus power at demand nodes are computed. Figure 5 shows the scatterplot between the total surplus power at the demand nodes and the resilience index [of *Todini*, 2000] of the networks. It can be noted from Figure 5 that an increase in the resilience index does not necessarily imply an increase in the total surplus power at the demand nodes (as indicated by a significant percentage of the network configurations). This shows that in case of networks with multiple sources, the resilience index may not be an accurate indicator of the total surplus power available at the demand nodes.

[66] The use of the modified resilience index proposed in this study circumvents the above problem by considering only the surplus powers at the demand nodes rather than the surplus power available for internal dissipation. As it can be seen, the modified resilience index increases as the diameter of links are increased from 300 mm to 500 mm as a result of the increase in the surplus output power with increase in the diameter. It is hence proposed to use the modified resilience index as an indicator of the ability of the network to handle uncertainties.

[67] The multiobjective optimal design and rehabilitation formulation was solved for the network described in the case example section using (1) the NSGA-II, (2) the proposed heuristic method, and (3) the combination of NSGA-II and the proposed heuristic method. The third method involves feeding in a reasonable number of the

Table 5. Chosen Values for NSGA-II Parameters[a]

NSGA-II Parameter	Chosen Value for NSGA-II	Chosen Value for Heuristic Plus NSGA-II
Generations	10000	2000
Population size	500	200
Crossover probability	0.8	0.8
Mutation probability	0.03	0.03
Distribution index for real-coded crossover	20	20
Distribution index for real-coded mutation	100	100

[a] Values are based on extensive sensitivity analysis.

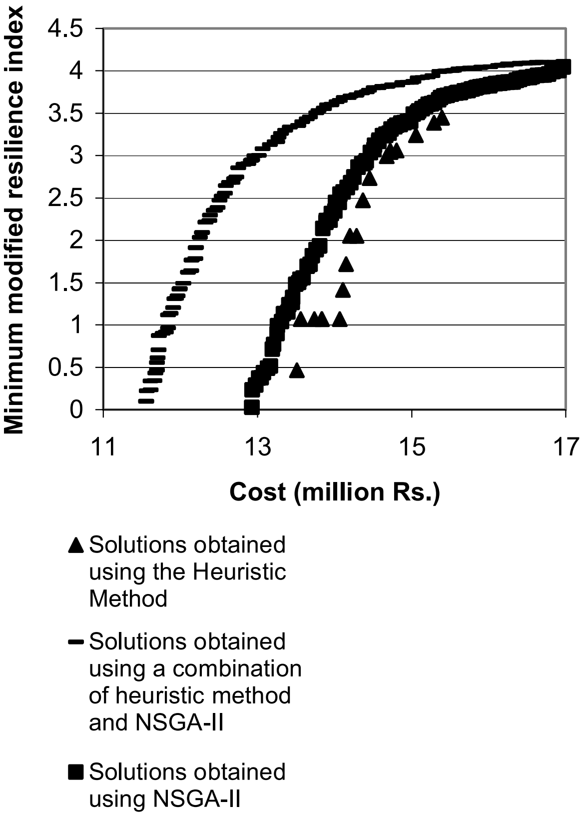

Figure 6. Comparison of the trade-off curves obtained using the NSGA-II, the proposed heuristic method, and the combination of the NSGA-II with the heuristic method.

solutions obtained using the heuristic method in to the initial population of the NSGA-II (with the rest of the solutions in the initial population set being randomly generated). An extensive sensitivity analysis was carried out to obtain the values for the NSGA-II parameters shown in Table 5. Figure 6 compares the tradeoffs between life cycle cost and minimum modified resilience index obtained using the three methods. It can be observed from Figure 6 that the solutions obtained using the heuristic method are reasonably close to the set of nondominated solutions obtained from the NSGA-II in terms of Pareto optimality. The NSGA-II took 52 hours of CPU time on a 3 GHz Pentium IV processor to produce the nondominated front for the run with a population size of 500 and 10,000 generations, while the heuristic method required only around 30 minutes. More interestingly, it can be seen from Figure 6, that the set of nondominated solutions obtained using the third method is much better than the set of nondominated solutions obtained using NSGA-II alone (method 1) or by using the heuristic method alone (method 2) in terms of the Pareto optimality. Moreover, method 3 consumed only 8 hours on the same processor mentioned above to produce the results, with a much lower population size of 200 and lesser number of generations (2000), compared to method 1, thereby resulting in considerable savings in computational time.

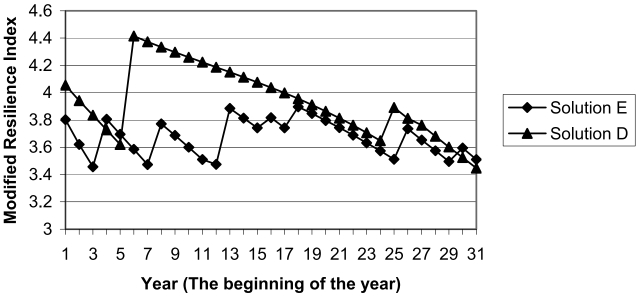

Figure 7. Comparison of the variation of modified resilience index values over the service life of solutions D (obtained using the heuristic method) and E (obtained using the combination of heuristic method and NSGA-II).

[68] We intend to show that the initial solutions obtained using the heuristic method have not biased the solutions from NSGA-II. For this purpose, two solutions D and E are selected from the fronts obtained using methods 2 and 3, respectively. Both these solutions possess a minimum modified resilience index value of 3.45 (Table 6). It can be seen that in case of the solution D, most of the links have been replaced in year 6, while in case of the solution E, the pipe replacements have been more staggered over the service life and not restricted to only the sixth year. This staggering of pipe replacements has also resulted in a reduction in the overall cost in case of the solution E (life

Table 6. Details About Solution D and Solution E[a]

		Pipe													
Solution	Parameter[b]	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
D	ID	400	200	100	150	100	200	250	100	200	100	100	100	250	300
D	YR	6	6	6	6	6	6	6	6	6	27	6	6	6	6
D	ND	400	300	150	300	150	300	350	150	300	150	150	150	300	400
D	CL1	25	-	-	-	-	-	-	-	-	-	-	-	-	-
D	CL2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
E	ID	400	300	100	150	100	150	300	100	200	100	100	100	200	250
E	YR	26	-	16	16	13	13	-	13	13	13	12	18	8	4
E	ND	400	300	100	200	100	300	-	100	250	100	100	200	350	400
E	CL1	-	-	-	-	-	-	-	-	-	-	-	-	-	30
E	CL2	-	-	-	-	-	-	-	-	-	-	-	-	-	-

[a] Details for solution D are selected from the solutions obtained using the heuristic method, and details for solution E are selected from the set of nondominated solutions obtained using the combination of the NSGA-II and the heuristic method. The minimum modified resilience index values of both solutions D and E equal 3.45. A dash implies that the pipe is not replaced.

[b] ID is the initial diameter of the pipe; YR is the year at which the pipe is replaced (pipes are replaced at the beginning of the year); ND is the new diameter of the pipe (after replacement); CL1 and CL2 are the 2 a in which the pipe is cleaned and lined. (pipes are cleaned and lined at the beginning of the years).

Table 7. Details About Solutions F, G, and H Selected From the Set of Nondominated Solutions Obtained Using the Combination of the NSGA-II and the Heuristic Method[a]

		Pipe													
Solution	Parameter	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14
F	ID	400	250	100	150	100	250	400	100	200	100	100	100	300	300
F	YR	26	8	19	13	12	13	-	11	18	13	8	-	7	4
F	ND	400	400	350	200	100	300	-	100	400	150	300	-	400	400
F	CL1	-	-	-	-	-	-	-	-	-	23	-	-	-	24
F	CL2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G	ID	400	250	100	150	100	250	350	100	200	100	100	100	300	300
G	YR	25	10	19	13	12	12	-	12	15	13	9	-	8	4
G	ND	400	350	300	150	100	300	-	100	300	100	300	-	400	400
G	CL1	-	-	-	-	-	-	-	-	-	-	-	-	-	30
G	CL2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
H	ID	400	250	100	150	100	200	300	100	200	100	100	100	250	250
H	YR	25	10	19	14	12	10	-	13	12	13	11	15	8	3
H	ND	400	350	250	200	100	300	-	100	300	100	100	250	400	400
H	CL1	-	-	-	-	-	-	-	-	-	-	-	-	-	29
H	CL2	-	-	-	-	-	-	-	-	-	-	-	-	-	-

[a]The minimum modified resilience index values of solutions F, G, and H are 4.1, 4.0, and 3.8, respectively.

cycle cost of Rs 13.68 million (Rs denotes Indian Rupees) as compared to the solution D (life cycle cost of Rs 15.73 million). Figure 7 shows significant variation of the modified resilience index values over the service period of 30 a between solutions D and E. This shows that the solutions obtained using the combination of the NSGA-II and heuristic method (method 3) are not biased by the solutions fed from the heuristic method (method 2). This is on expected lines since the heuristic method provides diverse solutions with the modified resilience index ranging from 0 to 3.5 and the corresponding life cycle cost ranging between Rs 13.5 million and Rs 15.5 million (corresponding to a diverse set of design and rehabilitation alternatives).

[69] With a view to illustrate that increasing the proposed modified resilience index leads to an increase in the uncertainty handling ability of the network, three solutions F, G and H (Table 7) have been selected from the set of nondominated solutions obtained using the combination of NSGA-II and the heuristic method. The maximum demand growth rate over the 30 a that these three networks can handle under increased roughness growth rate conditions is compared in Figure 8. It can be seen from Figure 8 that solution *F* (with the life cycle cost of Rs 16.86 million) with the minimum modified resilience index value of 4.1 can potentially handle much higher demand growth rates than solutions G (with the life cycle cost of Rs 15.53 million) and H (with the life cycle cost of Rs 14.57 million) that have lower values of minimum modified resilience index (4.0 and 3.8 respectively). This is a result of the additional surplus powers at the demand nodes in case of solution *F* as compared to solutions G and H. It is to be noted that the final selection of a solution might require a quantitative interpretation of the performance of solutions belonging to different ranges of minimum modified resilience index. This could be done by studying the network performance under different demands and pipe capacities (Figure 8) or by undertaking a Monte Carlo simulation where nodal demands and pipe roughness coefficients are treated as random variables.

[70] Finally, it is intended to compare the cost benefits that could accrue with the design and rehabilitation model as compared to the traditional model in which the network is optimally designed to handle demands that are expected to accrue after 30 a. In the traditional model, the network is designed to perform satisfactorily without a need for any rehabilitation action during the course of its service life. Hence the decision variables for this problem would be only the initial pipe diameters.

[71] Figure 9 shows the trade-off between total cost and minimum modified resilience index obtained assuming that the network would be overdesigned initially and wouldn't be rehabilitated or replaced during its entire service life. It can be seen that there is a massive cost difference at any value of minimum modified resilience index as compared to the solutions in the trade-off curve obtained using the combination of NSGA-II and heuristic method (Figure 9). For instance, the cost difference is to the tune of Rs 6.2 million (45% of the life cycle cost) for achieving a minimum modified resilience index of 3.4, Rs 4.5 million

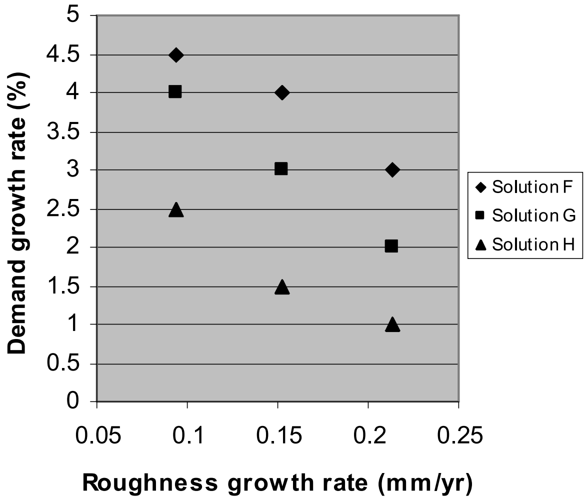

Figure 8. Comparison of the ability of the three solutions F, G, and H to handle increased demand growth rates and increased roughness growth rates (over the 30 a service period).

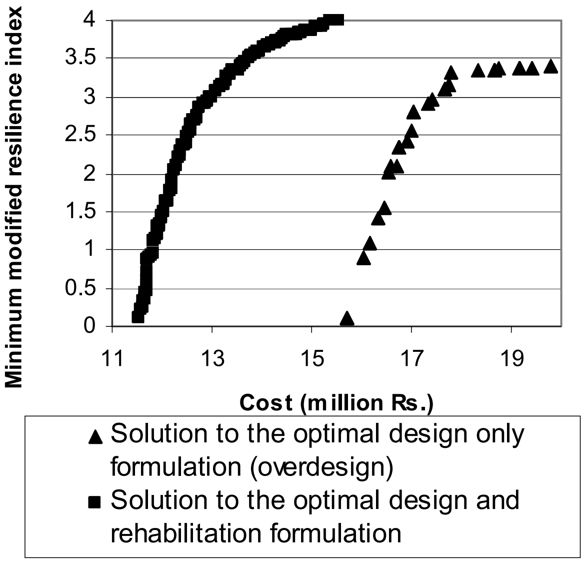

Figure 9. Comparison of the set of nondominated solutions obtained by solving the optimal design-only formulation (i.e., the network is not rehabilitated during the 30 a period) and the optimal design and rehabilitation formulation.

(34% of the life cycle cost) and Rs 4.3 million (35% of the life cycle) for achieving a minimum modified resilience index of 3.1 and 2.0 respectively. This shows that considering design and rehabilitation issues together would result in considerable cost savings as compared to overdesigning the network at the beginning of its service life.

7. Conclusions

[72] A new multiobjective formulation has been proposed for the optimal design and rehabilitation of a new network, with minimization of life cycle cost and maximization of minimum modified resilience index as objectives. The modified resilience index is a measure of the ability of the network to handle uncertainties and is a modified version of the resilience index defined by *Todini* [2000]. The modified resilience index circumvents the problems encountered by the resilience index of *Todini* [2000] when applied to multiple source systems. The nondominated sorting genetic algorithm of *Deb et al.* [2002] has been used to solve the constrained, multiobjective optimal design and rehabilitation problem. A new heuristic method has been proposed for the design and rehabilitation problem. It is found that feeding in the solutions obtained using the heuristic method in to the initial population set of the NSGA-II could direct the search process of the GA toward Pareto optimality in far less number of generations, thus effecting significant saving in computing effort and time. Using a sample network, it is illustrated that a network with a high value of minimum modified resilience index could handle uncertainties arising out of demand growths and pipe roughness growth rates during its service life better than a network with a lower value of minimum modified resilience index. Moreover, it has been illustrated that considering design and rehabilitation together would result in considerable cost savings as compared to overdesigning the network at the beginning of its service life, presuming that there will be no rehabilitation thereafter.

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